

# Ecohydrology and the Partitioning AET Between Transpiration and Evaporation in a Semiarid Steppe

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## ABSTRACT

Water availability defines and is the most frequent control on processes in arid and semiarid ecosystems. Despite widespread recognition of the importance of water in dry areas, knowledge about key processes in the water balance is surprisingly limited. How water is partitioned between evaporation and transpiration is an area about which ecosystem ecologists have almost no information. We used a daily time step soil water model and 39 years of data to describe the ecohydrology of a shortgrass steppe and investigate how manipulation of soil and vegetation variables influenced the partitioning of water loss between evaporation and transpiration. Our results emphasize the overwhelming importance of two environmental factors in influencing water balance processes in the semiarid shortgrass steppe; high and relatively constant evaporative demand of the atmosphere and a low and highly variable

precipitation regime. These factors explain the temporal dominance of dry soil. Annually and during the growing season 60–80% of the days have soil water potentials less than or equal to –1.5 MPa. In the 0–15 cm layer, evaporation accounts for half of total water loss and at 15–30 cm it accounts for one third of the loss. Annual transpiration/actual evapotranspiration (T/AET) ranged from 0.4–0.75 with a mean of 0.51. The key controls on both T/AET and evaporation/actual evapotranspiration in order of their importance were aboveground biomass, seasonality of biomass, soil texture, and precipitation. High amounts of biomass and late timing of the peak resulted in the highest values of T/AET.

**Key words:** ecohydrology; water balance; evaporation; transpiration; potential evapotranspiration; T/AET; E/AET; semiarid; steppe.

## INTRODUCTION

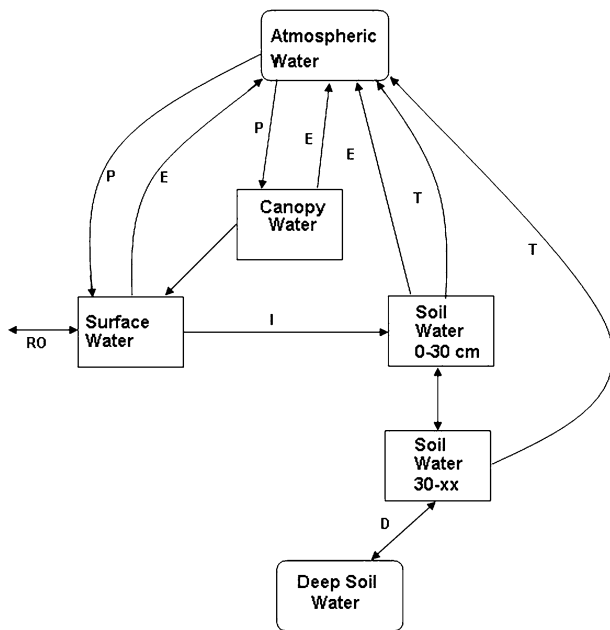
Water availability is a key control on ecosystem processes in arid and semiarid regions (Noy-Meir 1973). Precipitation, the major control on water availability, is an important explanatory variable for aboveground net primary production (Walter 1971; Lauenroth 1979; Sala and others 1988), net nitrogen availability (Burke and others 1997), decomposition, and carbon storage (Epstein and

others 2002). Understanding inputs, storages and losses of water in dry regions is crucial for understanding ecosystem processes under current conditions and will be of increasing importance under climate change (Schwinning and others 2004).

Although ecologists have long recognized the important role water plays in the structure and function of ecosystems in semiarid regions, there is surprisingly little information about the key processes in the water budgets of these systems (Figure 1). Prominent among these processes is the partitioning of water loss between evaporation and transpiration. Because leaf areas are low and bare

Received 28 April 2005; accepted 22 September 2005; published online 8 August 2006.

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**Figure 1.** Water balance diagram for an arid or semiarid ecosystem. P = precipitation, E = evaporation, T = transpiration, I = infiltration, RO = runoff/runon, D = loss or gain from deep soil water.

ground is an important component of the surface, only a portion of water stored in the soil is taken up by plants and returned to the atmosphere via transpiration. The remainder is lost as a result of the purely physical process of evaporation.

Precipitation, in the form of snow or rain, is either intercepted by live or dead plant material or it is deposited on the soil surface. Intercepted water, regardless of whether it is on live or dead plant material, is either evaporated back to the atmosphere or drips onto the soil surface. Water on the soil surface enters the soil, flows horizontally over the surface, or is evaporated back to the atmosphere. Water that enters the soil is either stored or moves through the soil and is lost as deep drainage. Stored water is evaporated or transpired back to the atmosphere depending upon where it is stored and the location of plant roots. The important controls on the fate of water received as precipitation are the amount of plant biomass (live and dead), the seasonality of biomass, topography (slope and aspect), and soil characteristics (primarily texture).

An annual water budget for a semiarid ecosystem can be represented as:

$$P = AET + \Delta S + RO + D. \quad (1)$$

Only two of the terms in this equation are easily evaluated empirically, **P** (precipitation) and  $\Delta S$  (change in soil storage). RO (run-off or run-on) is

very difficult to evaluate and **D** (deep drainage) is only slightly more tractable (Branson and others 1981). Actual evapotranspiration (AET), the combined evaporation and transpiration losses, can be evaluated with weighing lysimeters or recently by micrometeorological methods. A common assumption for semi-arid systems is that the net of both RO and D are sufficiently close to zero that they can be ignored (Bailey 1979; Shultz 1995; Falkenmark 1989). This reduces Equation (1) to:

$$P = AET + \Delta S. \quad (2)$$

Another common assumption is that, at an annual scale,  $\Delta S = 0$  (Ripley 1992) which reduces Equation (2) to:

$$P = AET. \quad (3)$$

Equation (3) suggests that all of the precipitation received at a semiarid location in a year is returned to the atmosphere as either evaporation or transpiration. The data that are available to independently assess Equation (3) are limited, although the recent increase in the availability of micrometeorological equipment to measure AET promises that we will have more information in the future. The widely observed fact that rivers do not arise in semiarid regions (Bailey 1979; Shultz 1995; Falkenmark 1989) lends credence to Equation (3).

Although increasing understanding of the terms in Equation (1) simply requires additional research attention, the challenge of separating the contributions of evaporation (E) and transpiration (T) to AET is a substantially more difficult problem. The most promising development recently is an indication that it may be possible to make this separation using isotopic methods (Ehleringer and others 2000). To date very little has been published on this E-T separation.

The objective of this manuscript is to evaluate the average daily and annual dynamics of the major components of the water budget including partitioning of evaporation and transpiration in a semiarid shortgrass steppe at the Central Plains Experimental Range in eastern Colorado, USA. We employed a daily time step soil water simulation model to address two objectives: (1) to describe daily and annual temporal patterns in components (potential evapotranspiration, actual evaporation, actual transpiration, soil water content) of the water budget at the Central Plains Experimental Range and (2) to evaluate how the partitioning of water loss between E and T varies with weather, soil texture, and the amount of biomass and its seasonality. Although simulation modeling has

many limitations, it is ideally suited to provide initial answers to questions that are very difficult or effectively impossible to address with current empirical methods (Shugart 2000; Canham and others 2003).

## METHODS

### Site Description

The Central Plains Experimental Range (CPER) is located approximately 60 km north-east of Fort Collins, Colorado and 30 km south of Cheyenne, Wyoming. The CPER is owned and operated by the Rangeland Resources Research Unit of the USDA Agricultural Research Service and is part of the Shortgrass Steppe Long Term Ecological Research site. Land surfaces at the CPER are typically level to gently sloping and soils are Aridic Argiustolls most often with sandy loam surface horizons (Yonker and others 1988). Mean annual precipitation is  $341 \pm 101$  mm (65-year mean and standard deviation), with 80% falling between April and September, and mean annual temperature is  $8.6 \pm 0.6^\circ\text{C}$  (Lauenroth and Sala 1992). The vegetation is dominated by  $C_4$  shortgrasses blue grama (*Bouteloua gracilis*) and buffalo grass (*Buchloe dactyloides*) although on particular sites or years with wet springs,  $C_3$  grasses can make important contributions to aboveground net primary production. Other important plant types include forbs, dwarf shrubs, and prickly pear cactus (*Opuntia polyacantha*) (Milchunas and others 1989). Average annual aboveground net primary production is  $97 \text{ g/m}^2$  with a 52-year range of  $62\text{--}143 \text{ g/m}^2$  (Lauenroth and Sala 1992). Aboveground standing crop biomass ranges from 77 to  $379 \text{ g/m}^2$  depending on species and lifeform composition and water availability (Sims and others 1978; Liang and others 1989).

### Model Description

We used SOILWAT, a daily time-step soil water model developed for shortgrass steppe ecosystems (Parton 1978). SOILWAT requires input information about initial soil water conditions, weather, vegetation, and soil properties (see Appendix tables, <http://www.Springerlink.com>). Weather inputs include daily precipitation and maximum and minimum temperatures, and monthly relative humidity, wind speed and cloud cover. Vegetation inputs are monthly estimates of aboveground biomass, litter and the proportion of aboveground biomass that is live. Soil properties for each soil layer consist of texture, bulk density, field capacity,

wilting point and relative proportions (relative to the entire soil profile) of evaporation and transpiration.

From these input values, SOILWAT simulates water interception and subsequent evaporation by the plant canopy and litter layer, water infiltration into the soil, water flow among soil layers, evaporation and transpiration from each layer and soil water content by layer. A description of SOILWAT is presented in Parton (1978) and examples of applications in Lauenroth and others (1993, 1994), and Coffin and others (1993). Because we simulated one of the most common soils at the CPER using average soil physical properties, our simulations do not represent any specific location and therefore comparisons to data are difficult. We have previously published a comparison of simulated soil water for 5 locations with sandy loam soils (Lauenroth and others 1994). The model explained 66% of the variability in these data.

### Water Dynamics Under Normal Conditions

We simulated soil water dynamics in nine layers (0–7.5 cm, 7.5–15 cm, 15–30 cm, 30–45 cm, 45–60 cm, 60–75 cm, 75–90 cm, 90–120 cm, and 120–150 cm) for the most common soil type (Ascalon sandy loam) at the CPER under normal vegetation conditions (Lauenroth and Milchunas 1992) for 39 years (1964–2002). We calculated daily averages and daily coefficients of variation (39 values for each day) as well as grand daily coefficients of variation (365 times 39 values for each variable) over the 39 years for potential evapotranspiration (PET), precipitation, soil water content to a depth of 45 cm (SWC), actual evapotranspiration (AET), transpiration, evaporation (from soil, standing vegetation and litter) and the ratio of transpiration to AET (T/AET) (Table 1). Soil water content estimates were used to determine cumulative relative frequency distributions of daily SWC for both the growing season (April–September) and the non-growing season (October–March) as well as the proportion of days with soil water content below wilting point in winter (December–February), Spring (March–May), Summer (June–August) and Fall (September–November). To characterize temporal relationships between precipitation events and soil water content we examined daily dynamics in these estimates for a year with nearly average precipitation and temperature. We also calculated correlation coefficients between daily soil water content in the top four soil layers (Table 2) and daily precipitation for 3 years with approximately

**Table 1.** Coefficients of Variation associated with Grand Daily Means of Key Water Balance Processes over 39 Years

Variable	Coefficient of Variation (%)
Precipitation	333
Temperature	295
PET	17
AET	92
Transpiration	46
Evaporation	135
T/AET	60
SWC-45	24

**Table 2.** Correlation Coefficients for the Relationship between Daily Soil Water Content in 4 Layers and Precipitation in 3 Average, 3 Wet and 3 Dry Years

Soil Layer (cm)	Average	Wet	Dry
0–7.5	0.336	0.443	0.349
0–15	0.365	0.504	0.272
0–30	0.399	0.478	0.209
0–45	0.350	0.401	0.154

*All of the correlation coefficients are significant at  $P < 0.01$ .*

average precipitation, 3 years with low precipitation and 3 years with high precipitation.

To examine annual soil water dynamics we summed daily estimates for all 39 years and calculated annual averages and standard deviations for precipitation, canopy interception, canopy evaporation, infiltration, percolation between soil layers and both evaporation and transpiration from each layer. We assumed that the net of surface water runoff and runoff is zero in this semi-arid system (Bailey 1979; Shultz 1995; Falkenmark 1989). We determined the proportion of AET from transpiration (T/AET) and soil evaporation (E/AET) for all 39 years. Using these estimates we calculated the relative frequency distribution of T/AET and conducted linear regressions of both T/AET and E/AET on annual precipitation.

### The Influence of Soil and Vegetation on Evaporation and Transpiration

To understand controls over the balance between evaporation and transpiration we varied soil texture, aboveground biomass and biomass seasonality. Soil textures included in the simulations were sandy loam, loam and clay. Aboveground biomass

was varied by multiplying the normal monthly biomass and litter by 0.5 for low biomass and 2.0 for high biomass. Variation in biomass seasonality was implemented by moving monthly values for biomass, litter and percent live 2 months earlier and later for early and late seasonality, respectively. We simulated daily evaporation and transpiration between 1964 and 2002 for 27 scenarios defined by 3 soil types, 3 levels of aboveground biomass (low, normal and high) and three levels of biomass seasonality (early, normal and late). To quantify the influence of weather, soil and vegetation characteristics on partitioning between transpiration and evaporation we conducted an analysis of variance on annual values of T/AET and E/AET with main effects and all two-way interactions of precipitation, soil texture, biomass and seasonality. Because our simulation had no true random processes, we limited our interpretation of the analysis of variance results to the ranking of the mean squares (Steinhorst and others 1978).

## RESULTS

### Average Water Balance of a Sandy Loam Site

**Daily Dynamics.** Atmospheric demand, represented by potential evapotranspiration (PET), exceeded water input (precipitation) by a factor of 3 in the spring and summer wet season and by a factor of 10 or more during the winter dry season (Figure 2a, b). Because the wet season is also the warm season, PET and precipitation were highly correlated through time ( $r = 0.71$ ). The maximum and minimum in PET corresponded closely with the maximum and minimum in precipitation. Maximum PET occurred in June and July and minimum occurred in December and January. Maximum precipitation occurred in May and June and minimum occurred in December and January. The variability associated with average daily precipitation was very large compared to PET (Figure 2a, b). Coefficients of variation (CV) for daily precipitation in mid-summer were mostly in the range of 200–400% whereas in the winter they were between 300 and 700%. By comparison, CVs associated with PET were between 5 and 15% during the summer and 20–40% in the winter (Figure 2a). The coefficient of variation of average daily PET over the 39 years was 17% compared to 333% for daily precipitation (Table 1).

Average daily soil water in the top 45 cm changed very little over the annual cycle (Figure 2c). Both the lowest and highest values occurred during

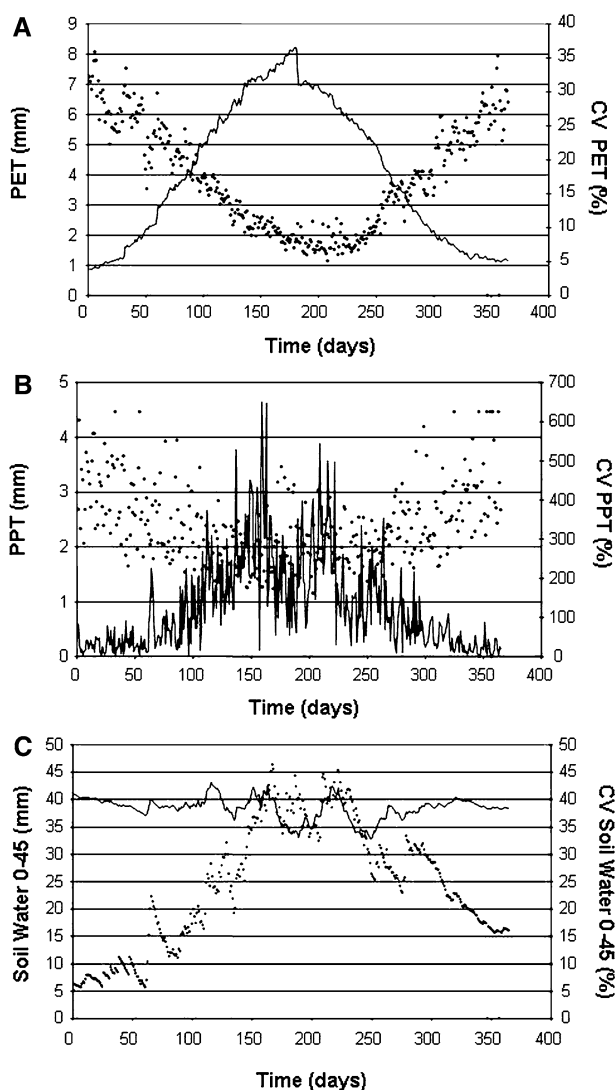


Figure 2. Daily averages and coefficients of variation (CV) for potential evapotranspiration (PET), precipitation (PPT), and soil water content in the 0–45 cm layer for 39 simulated years at the Central Plains Experimental Range. The means are represented by *lines* and the coefficients of variation by *dots*.

the wet season, which is also the season of maximum PET. The lowest values were between 32 and 35 mm and the highest were between 40 and 43 mm. Although these averages attenuated the dynamics of individual years, they suggest that the most common state for the soil is dry. A year that received the average amount of precipitation (1968) provides a good example of the dynamics of soil water to be expected in a single year (Figure 3). Soil water in the 0–45 cm layer was closely related to precipitation and individual pulses of soil water were of relatively short duration especially during the warmest season (days 120–240). Before and

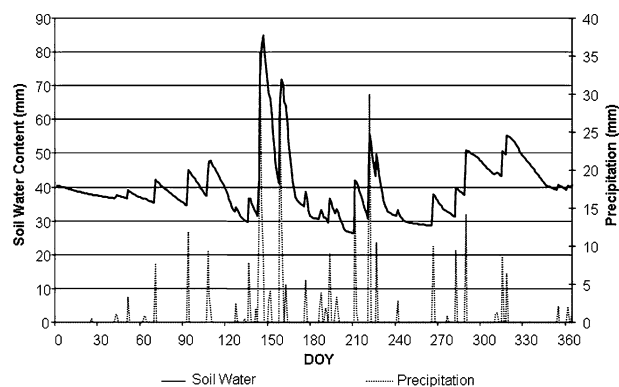


Figure 3. Daily soil water and precipitation for 1968, a year that received an average amount of precipitation.

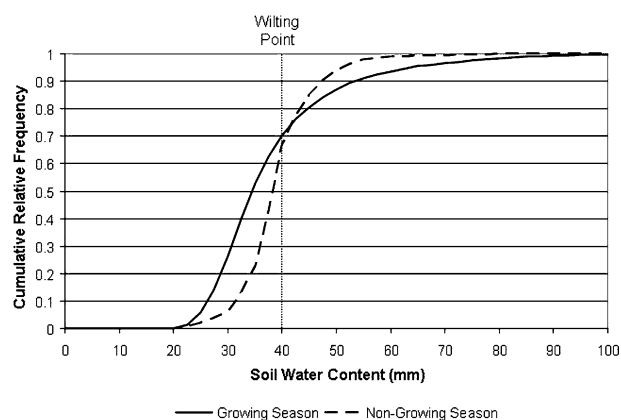


Figure 4. Cumulative relative frequency of the proportion of days in 39 years with soil water contents greater than or less than wilting point (corresponding to  $-1.5$  MPa). The days were separated into growing season days (April–September) and non-growing season days (October–March).

after this period, soil water pulses lasted longer because of comparatively low PET. This single year's data also emphasized the major message of the long-term average data: the background condition of dry soil is interrupted infrequently by short periods of wet soil.

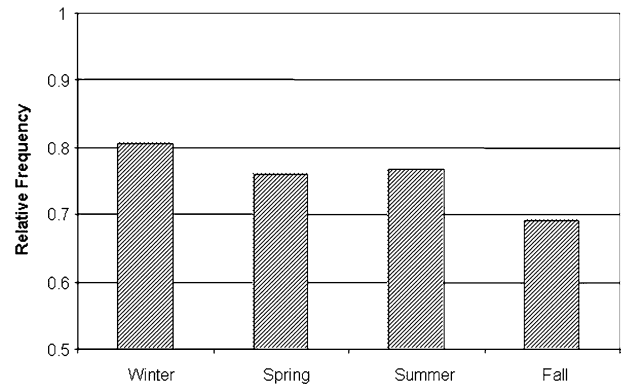
During the potential growing season (April–September), 70% of the days, over the 39 years of observations, had soil water contents less than or equal to wilting point [We used 11% ( $-1.5$  MPa the agronomic standard for wilting point) for this calculation because we do not know the actual value for shortgrass steppe species and in these sandy loam soils 80% of the water held in the soil between  $-0.03$  and  $-10$  MPa has been lost by the time they reach  $-1.5$  MPa] (Figure 4). On average, 55 of the 183 growing-season days each year had

soil wetter than wilting point. During the non-growing season (October–March), 67% of the days had soil water contents less than or equal to wilting point. On a seasonal basis, winter had the highest frequency of days with water contents equal to or less than wilting point and fall had the lowest, although the difference between them was only 11 percentage points (Figure 5).

The relationship between average daily soil water content and precipitation was significant, but variable depending upon the soil layer and whether the year was wet, average, or dry (Table 2). The highest correlations were for wet years and soil layers between 0 and 30 cm. The lowest correlations were for the deepest layers during the dry years. The CVs of daily soil water (0–45 cm) were substantially smaller than those for precipitation and comparable to those for PET. CVs ranged from 5–15% for the dry season and 25–45% for the wet season (Figure 2c). The CV associated with the 39-year grand daily mean of soil water content (0–45 cm) was 24% (Table 1).

The annual cycle of mean daily actual evapotranspiration (AET) has the characteristics of a smoothed version of the annual precipitation curve (Figure 6a). Peaks occurred in May–June and late July early August corresponding with peaks in precipitation. Minimum values occurred in December and January associated with minima in precipitation. Maximum AET was between 2 and 3 mm/day in June and late July and the minimum was less than 0.25 mm/day in late December and early January. Coefficients of variation of average daily AET ranged from 60–160% with no clear wet season-dry season pattern. The CV of the 39 year average daily AET was 92% (Table 1).

The dynamics of both daily average transpiration and daily average evaporation also reflected the annual cycle of precipitation inputs (Figure 6b, c). Transpiration was concentrated during April through October, the period that has the highest likelihood of being favorable for green leaf area, although there is a small amount of green leaf area in the other months and therefore a very small amount of transpiration (Figure 6b). Maximum values of transpiration ranged from 1.0 to 1.8 mm/day. The CV of average daily transpiration varied from 20 to 60% during the dry season and between 40 and 130% in the wet season. Evaporation occurred every day of the year and was primarily limited by precipitation (Figure 6c). Maximum evaporation occurred during the wet season and ranged from 0.6 to 1.2 mm/day. During the dry season, evaporation ranged from 0.1 to 0.5 mm/day. CVs of evaporation ranged from 50 to 225%



**Figure 5.** Relative frequency of days during each season with soil water contents equal to or less than wilting point (corresponding to  $-1.5$  MPa) for 39 simulated years at the Central Plains Experimental Range.

without a clear wet season-dry season pattern. The 39-year coefficients of variation for transpiration and evaporation were 46 and 135%, respectively.

The daily average ratio of  $T/AET$ , representing the proportion of the total water loss that was accounted for by transpiration, was near zero in the winter and as high as 0.8 in the middle of the growing season (Figure 6d). Wet season  $T/AET$  ranged from 0.6–0.8. Coefficients of variation for the wet season ranged from 20 to 60% and for the dry season from 40 to 160%. The CVs for the 39-year average daily  $T/AET$  was 60% (Table 1).

**Annual Averages.** Average annual PET over the 39 years was 1,483 mm with a range of 1,372–1,586, and the ratio of annual average precipitation to annual average PET was 0.23. The average annual precipitation was 335 mm and ranged from a low of 107 mm in 1964 to high of 588 mm in 1967. An average of 15% of the precipitation was intercepted by the canopy and returned to the atmosphere by evaporation and 85% entered the soil (Figure 7). Forty percent of the 286 mm that entered the 0–15 cm layer of the soil was evaporated back to the atmosphere, 40% was transpired and 19% percolated to the 15–30 cm layer. Evaporation from the 15–30 cm layer accounted for 27% of the water entering it, transpiration accounted for 51 and 22% percolated to the deeper layers. The water that was transpired from the layers deeper than 30 cm represented 125% of that entering the layer. The extra 3 mm/year lost from these layers represented water from the initial conditions. No water percolated to the deep soil water.

On an annual basis,  $T/AET$  ranged from a low of 0.37 to a high of 0.73 with a mean of 0.51 (Figure 8).  $T/AET$  was lowest in the wettest years and highest in the driest years suggesting that the

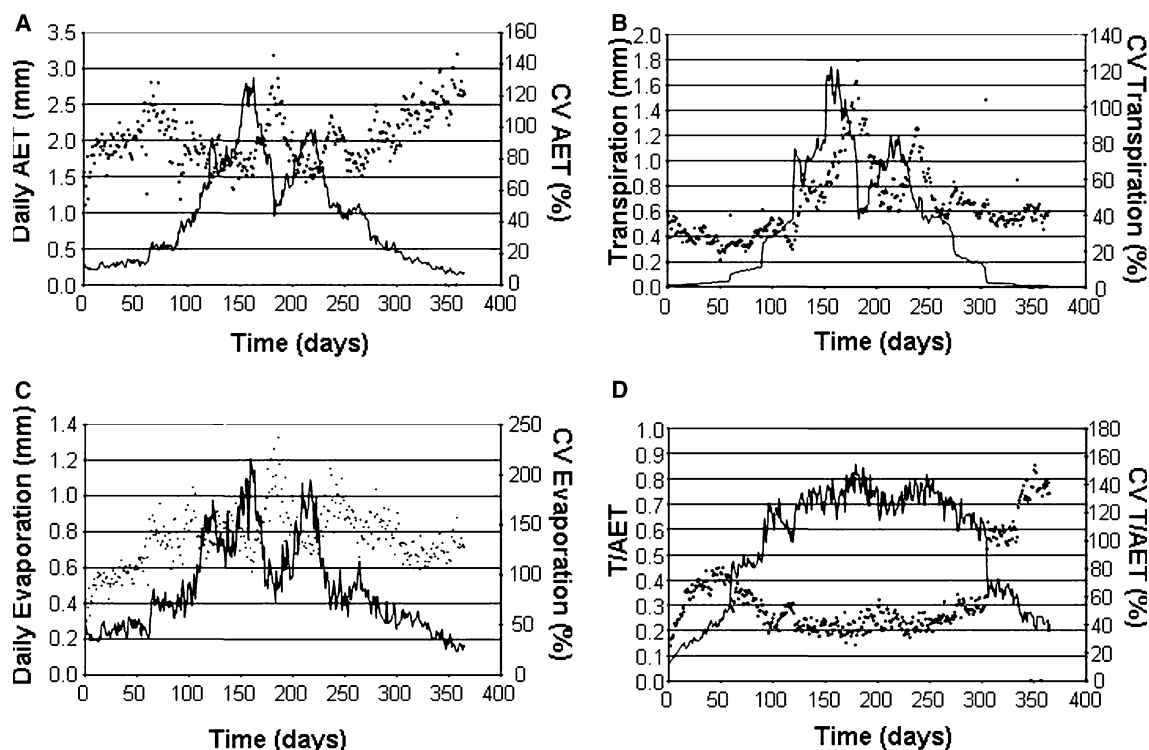


Figure 6. Means and coefficients of variation (CV) of average daily. (A) actual evapotranspiration (AET), (B) transpiration (T), (C) evaporation (E), and (D) the ratio of transpiration to evapotranspiration (T/AET) for 39 simulated years at the Central Plains Experimental Range. The means are represented by solid lines and the coefficients of variation by dots.

combination of canopy interception and evaporation and bare soil evaporation increased faster as precipitation increased than did transpiration. Regression of E and T against annual precipitation confirmed this relationship. The slope coefficient for E was 0.69 ( $r^2 = 0.64$ ) and for T was 0.24 ( $r^2 = 0.93$ ).

### Effects of Texture, Biomass and Seasonality on Transpiration and Evaporation

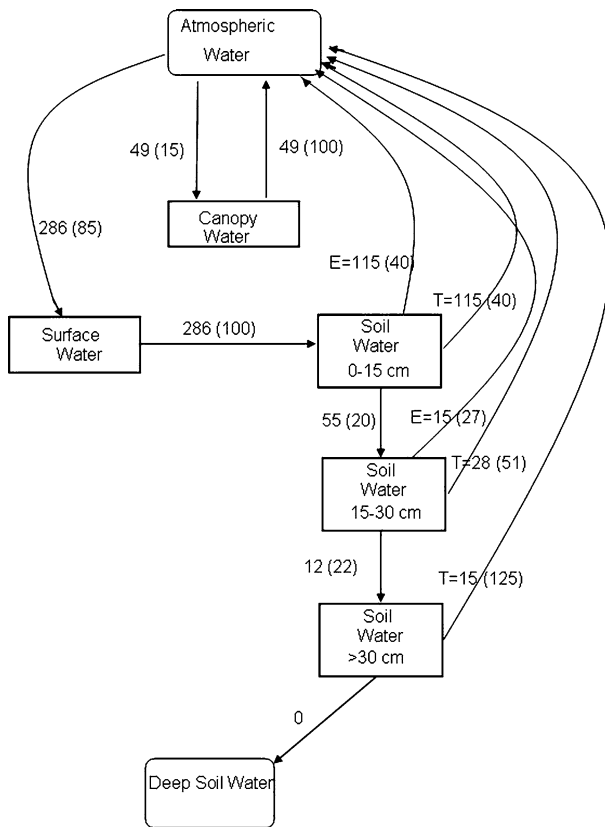
The factorial combination of precipitation, season of peak biomass, amount of peak biomass and soil texture resulted in a clear ordering of main effects and no important interactions (Tables 3, 4). The major influences on both T/AET and E/AET in order of importance were biomass, seasonality, soil, and precipitation. The amount of biomass was the single most important factor influencing both T/AET and E/AET. The largest values of T/AET were associated with an average amount of biomass and both higher and lower biomass resulted in a smaller proportional contribution of transpiration to total

water loss although the high biomass was only slightly lower than average (Figure 9a). The highest biomass was associated with the lowest values of E/AET, average biomass produced a larger E/AET and the lowest biomass had the highest (Figure 9b). Average timing of the peak biomass had the largest values of T/AET and earlier and later peaks had lower values (Figure 9c). Late timing of the biomass peak resulted in the highest E/AET and early and average peaks were lower and very similar (Figure 9d). Soil texture had small effects on both T/AET and E/AET with sandy loam and loam having essentially identical values and clay having lower T/AET and higher E/AET (Figure 9e, f).

## DISCUSSION

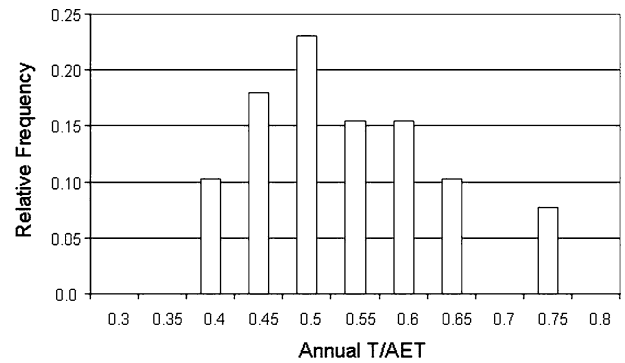
### Daily Average Perspective

The interaction between evaporative demand (PET) and precipitation determine the key characteristics of the ecohydrology of the shortgrass steppe. Over the entire annual cycle, PET is high relative to precipitation and comparatively invari-



**Figure 7.** Simulated 39-year annual average amounts (mm) and percentages (in parentheses) of the major components of a shortgrass steppe water budget. The percentages were calculated relative to the compartment from which the water was derived.

ant (Figure 2). Precipitation is low on a daily, growing season and annual basis. On an annual basis, there is an average of 75 daily precipitation events per year and only 20 of them are greater than 5 mm. More than 70% of wet season daily precipitation amounts are below 5 mm and they contribute approximately 25% of the precipitation (Sala and Lauenroth 1982). One of the results of a precipitation regime numerically dominated by small events is that all of the water deposited by those events remains in the layers most heavily influenced by bare soil evaporation (Sala and Lauenroth 1985; Sala and others 1992; Wythers and others 1999). This is exacerbated by the coincidence of the warm season and the wet season, which results in the wet season also being the season of highest PET (Figure 2). The abundance of small precipitation events and the overlap between the warm and wet seasons are the most important explanatory variables for the shallow spatial distribution of soil water in the shortgrass steppe. Sala and others (1992) found that the 4–15 cm soil layer



**Figure 8.** Relative frequency of annual simulated T/AET for a shortgrass steppe.

had the highest frequency of plant available water over a 30 year analysis regardless of whether the year was dry, wet or average.

In addition to a shallow distribution of soil water, the variability in average daily soil water content is high, especially for water contents above wilting point. The CV of total soil water in the 0–45 cm soil layer is 26%, but if the approximately 70% of the days with water contents at or below wilting point (corresponding to  $-1.5$  MPa) are removed the CV of average daily soil water content rises to 277%. This suggests that water is moving into and out of the soil very rapidly. The reasons for this rapid cycling and resultant temporal variability are: (1) the inputs are temporally highly variable (Figure 2, Table 1); (2) the large majority of inputs are small and only wet the layers that are simultaneously influence by both evaporation and transpiration; and (3) PET is large and relatively constant, which allows for rapid losses back to the atmosphere (Figure 2, Table 1). The rapid cycling of water into and out of the soil is a key characteristic of shortgrass steppe soil water dynamics and may also be for other semiarid ecosystems. The fact that the correlation between daily precipitation and daily soil water is less than 1 (Table 2) indicates that soil properties play a role in introducing time lags in soil water dynamics.

The average length of time between precipitation events at the CPER is 7 days and is consistent throughout the annual cycle (Wythers and others 1999). The average potential amount of water that could be lost during a 7-day period in the fall and winter (non-growing season) is 14 and during the April–September growing season is 44mm. Although water is rarely available to be lost from the soil at these potential rates, they provide perspective on this important aspect of the shortgrass environment. They also suggest an explanation for

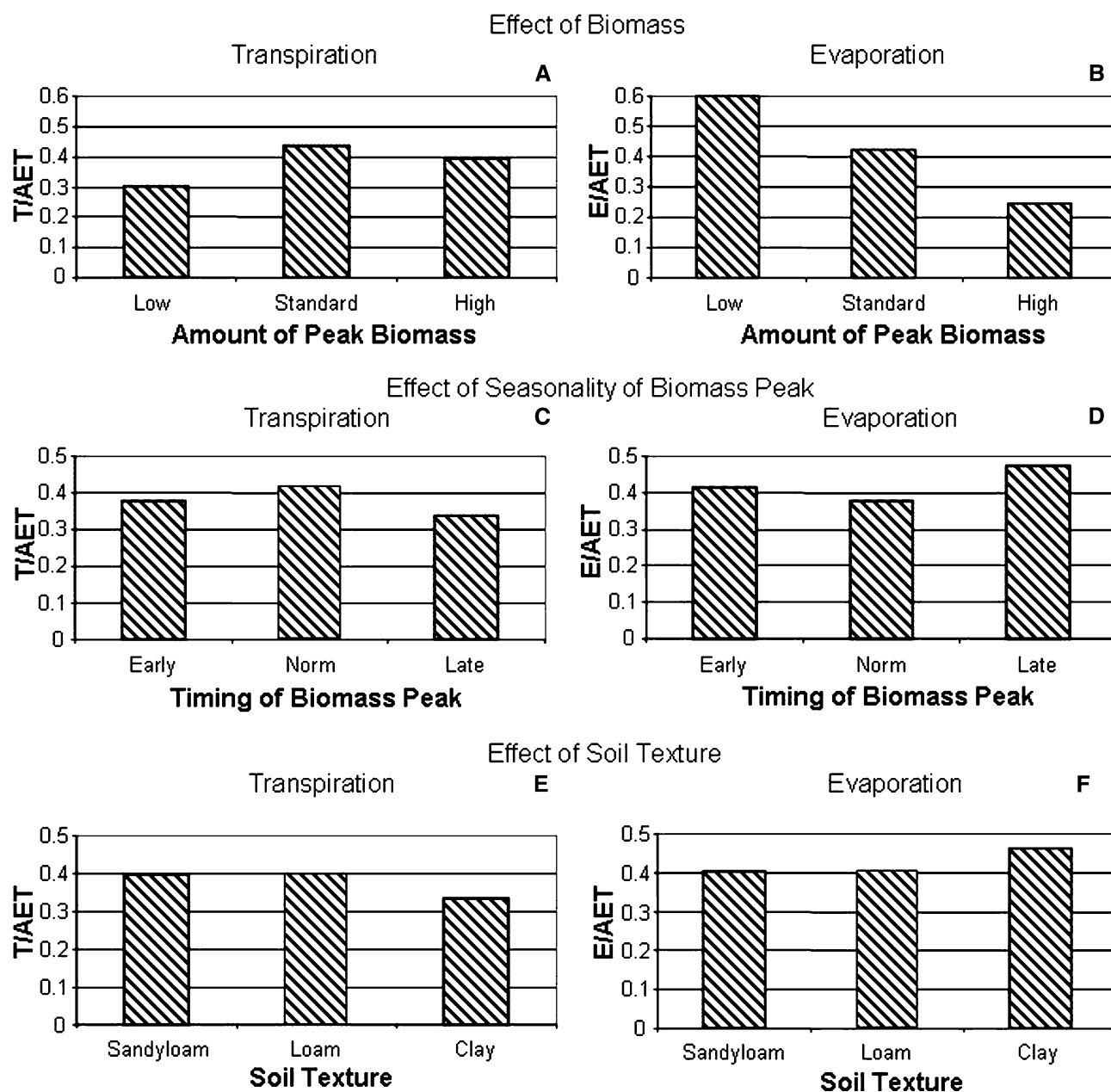


Figure 9. Effects of biomass (A, B), seasonality of biomass (C, D), and soil texture (E, F) on the ratio of transpiration to actual evapotranspiration (T/AET) and the ratio of evaporation to actual evapotranspiration (E/AET) for a shortgrass steppe.

why it is very difficult to store water below 15 cm during the middle of the growing season (Sala and others 1992).

Average daily AET, transpiration, and evaporation were all significantly correlated ( $P < 0.01$ ) with average daily precipitation with coefficients of 0.50, 0.55, and 0.46, respectively. Because PET is such an important driver of water loss and for all of the reasons mentioned above, this relationship is not surprising. The most important question about these results is whether the partitioning of AET

between transpiration and evaporation is reasonable. Although, we know of no objective, conclusive answer to this question, there are data that suggest our results are reasonable. Wythers and others (1999) reported results from a bare soil evaporation field experiment from the Central Plains Experimental Range. Their experiment used 20 cm diameter by 40 cm deep lysimeters filled with either sandy loam, silt loam or clay loam soil. The lysimeters were brought up to field capacity and then allowed to lose water via bare soil evap-

**Table 3.** Analysis of Variance Table for the Ratio of Transpiration to Actual Evapotranspiration (T/AET)

Source	DF	Sum of Squares	Mean Square
Precipitation	38	291.18	7.66
Season	2	107.03	53.52
Biomass	2	318.50	159.25
Soil	2	91.68	45.84
Season*Soil	4	5.70	1.42
Precipitation*Soil	76	50.02	0.66
Precipitation*Biomass	76	60.90	0.80
Biomass*Soil	4	6.28	1.57
Season*Biomass	4	4.83	1.21
Precipitation*Season	76	76.27	1.00

**Table 4.** Analysis of Variance Table for the Ratio of Evaporation to Actual Evapotranspiration (E/AET)

Source	DF	Sum of Squares	Mean Square
Precipitation	38	517.09	13.61
Season	2	156.76	78.38
Biomass	2	2169.32	1084.66
Soil	2	85.16	42.58
Season*Soil	4	6.21	1.55
Precipitation *Soil	76	54.67	0.72
Precipitation *Biomass	76	38.90	0.51
Biomass*Soil	4	6.86	1.72
Season*Biomass	4	9.86	2.46
Precipitation *Season	76	97.90	1.29

oration. They simulated their experimental results using the same soil water model we used and found that for the first 8 days, the model estimated 31 mm of evaporation when the true loss was 35 mm. Eight days is a critical time period because it is approximately the average interval between precipitation events at the CPER (Wythers and others 1999). Their maximum measured daily bare soil evaporation rates from sandy loam soil at field capacity were near 9 mm. Our maximum daily evaporation rates were 3.8 mm for bare soil and 6.7 mm for total evaporation including all of the interception terms. Compared to the Wythers and others (1999) experimental results, our evaporation rates are low and therefore we may have underestimated total evaporation losses compared to transpiration.

Ferretti and others (2003) reported an assessment of the partitioning of AET into T and E for the CPER using stable isotopes. Their daily evaporation

rates were largest during the non-growing season, but always less than 1 mm. Daily transpiration rates ranged up to greater than 4 mm during the growing season. Our maximum daily transpiration rates were between 2.8 and 3.1 mm and always occurred at the end of May or the beginning of June, which is the peak of the wet season.

## Annual Perspective

Shallow soil water dynamics and the huge potential of the atmosphere to evaporate water explains why AET is approximately equal to precipitation on an annual basis. The correlation of annual precipitation and AET from our 39 years of simulation was 0.99 even though the model contained no constraints requiring that these quantities be equal. The environment provides such overwhelming constraints it is virtually impossible for this relationship to be different. The average annual PET is 1,483 mm and the average annual precipitation is 335 mm. Equation (1) indicates that deviations from  $P = AET$  must originate with soil water storage, runoff or deep drainage. Dodd and Lauenroth (1997) measured soil water content down to 120 cm in a loamy sand, sandy clay loam and sandy clay over 5 years and found that out of the 60 layer  $\times$  year  $\times$  soil texture combinations in only two cases was soil water content greater than 5% at the end of the year. This suggests that soil water storage is not a likely source of deviations from  $P = AET$ . Runoff is not a common event in the shortgrass steppe. It is widely recognized that rivers do not originate in mid-latitude semiarid regions such as the North American shortgrass steppe (Falkenmark 1989; Shultz 1995). The importance of small precipitation events precludes anything but short distance runoff under all but the most extreme conditions. The predominantly shallow distribution of soil water also suggests that deep drainage is not an important component of the water balance. In the 36 years that the 1 m deep weighing lysimeter has been monitored at the CPER, there has never been any water captured in the deep drain catchment. Therefore  $P = AET$ , on an annual basis, is a reasonable expectation for the shortgrass steppe.

The partitioning of water loss between evaporation and transpiration is one of the most poorly understood processes in ecohydrology. Ferretti and others (2003) used stable isotopes to partition T and E at the CPER and found that over 3 years of measurement that evaporation accounted for 0–40% of total water loss during the May through September growing season. Our

results over 39 years indicated that daily average  $E$  accounted for 42% and  $T$  for 58% of total water loss. On an annual basis we found that  $E$  accounted for 51% of total water loss and  $T$  for 49%. The importance of  $T$  in the shortgrass steppe is relatively high for semiarid ecosystems. Other investigators have reported values for  $T$  as a percentage of total water loss ranging from 30–70% to total water loss (Paruelo and Sala 1995; Floret and others 1982; Ng and Miller 1980; De Jong and Hayhoe 1984; Wight and others 1986; Reynolds and others 2000). Reynolds and others (2000) reported a 100 year average  $T/AET$  for Chihuahuan desert grasslands and shrublands of 34%, but found a range from 1–58% for the grassland sites and 6–60% for the shrubland sites. Our 39 year range of values for  $T/AET$  was 37–73%.

Both Paruelo and Sala (1995) and Reynolds and others (2000) found positive relationships between annual bare soil evaporation or total evaporation losses and annual precipitation. We also found a positive relationship between evaporation, either bare soil or total and annual precipitation. In addition, we observed a positive relationship between transpiration loss and annual precipitation as did Reynolds and others (2000). One of the differences between our results and those of Reynolds and others (2000) is that they found a positive relationship between  $T/AET$  and annual precipitation and ours was negative. The explanation for our finding is that evaporation increases as a function of precipitation faster than transpiration. The slope of the  $T$  versus annual precipitation relationship was 0.24 ( $r^2 = 0.64$ ) whereas the slope for  $E$  was 0.69 ( $r^2 = 0.93$ ). The component of  $E$  that accounted for the major increase as precipitation increased was bare soil evaporation. An important difference between the Reynolds and others (2000) model and ours is that the Reynolds model simulates plant biomass, which presumably changes among years as precipitation changes. Our model uses the same biomass curve and timing of peak biomass regardless of annual precipitation. This should lead our model to underestimate  $T$  in wet years and overestimate it in dry years. Our sensitivity experiment indicated that the amount of biomass was an influential control on both  $T/AET$  and  $E/AET$ .  $E$  decreased as biomass increased although transpiration was greatest at the average amount of biomass not at the highest value (Figure 9). The reason  $T$  did not increase from average to high biomass was that interception losses increased as biomass increased and accounted for 35% of water loss at the highest biomass compared to 10% at low biomass.

## CONCLUSIONS

Our results complement past work on the shortgrass steppe and other semiarid and arid ecosystems and add substantially to the understanding of the water budget of water controlled ecosystems (Noy-Meir 1973). Two environmental factors overwhelmingly dominate the water balance of the shortgrass steppe; high and relatively invariant evaporative demand of the atmosphere and a precipitation regime that is characterized by small annual, seasonal, and daily amounts (Figure 2). At a daily scale, these factors explain the predominance of dry soil (Figure 2). Seasonally and annually 60–80% of the days have soil water contents below wilting point (amount corresponding to  $-1.5$  MPa) (Figures 4, 5). At an annual scale, they explain the large importance of evaporation. In the 0–15 cm soil layer, evaporation accounts for half of the annual water loss and slightly more than a third of the water loss from the 15–30 cm layer. On an annual basis, water loss is approximately equally divided between evaporation and transpiration. It is clear from our work and its antecedents that from an ecosystem perspective the shallow soil layers (0–45 cm) are the most dynamic portion of shortgrass steppe soil. Factorial manipulation of aboveground biomass, suggested that aboveground biomass and its seasonality are the key controls on transpiration and evaporation.  $T/AET$  and  $E/AET$  were maximized by high biomass that peaked late in the growing season.

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